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Research Paper

Large-scale field evaluation of driving performance and ergonomic effects of satellite-based guidance systems

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Positive driving performance and ergonomic effects are ascribed to satellite-based automatic guidance systems. Although the literature had provided some information on working-width utilisation, turning-time requirement and steering accuracy, the relevant studies had mostly been carried out on smaller areas of land under experimental conditions. Little information was found on the nearly-always-mentioned reduction in driver workload. A large-scale field trial under practical conditions was carried out in the Czech Republic for the expanded clarification of the driving-performance and ergonomic effects of automatic guidance systems. Various parameters were recorded for 17 drivers with respect to primary tillage, seedbed preparation and sowing both with and without a guidance system. Working widths were between 5 and 15 m, and field sizes between 1.2 and 15.7 ha. The findings showed that driving speeds, turning times and working-width utilisation were in some cases more advantageous with a guidance system, but did not differ statistically significantly. The variations caused by driver, field shape and field margins had a greater influence than the use of guidance systems. Two parameters differed significantly, however. Guidance systems increased the average steering accuracy and delivered a lower heart rate. The study confirmed that guidance systems can deliver positive driving-performance effects and can contribute to driver relief.

1. Introduction

The benefits of satellite-based automatic guidance systems used on tractors and harvesters are chiefly said to reside in the optimal utilisation of vehicle working widths and in driver relief. These in turn are said to result in less overlap and double tillage, a reduction in the amount of plant-protection products and fertilisers required, and lower field-work times than for manual steering. In addition, turning times can be reduced by optimised lane management, and working in the

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dark can be made substantially easier (Demmel, 2007; Macak & Nozdrovicky, 2011; Niemann, Schwaiberger, & Fröba, 2007; Rüegg, Total, Holpp, Anken, & Bachmann, 2011; Schulten-Baumer, Schmittmann, & Schulze Lammers, 2009).

Small-scale Austrian studies showed a reduction in turning time of 3.3 s or 15% in the case of tillage with a 4.2 m-wide disc harrow (Moitzi, Heine, Refenner, Paar, & Boxberger, 2007). Under larger-scale conditions in the Czech Republic, the turning time was reduced by 5% with the use of guidance systems (Kroulik, Loch, Kviz, & Prosek, 2009). In Bavarian studies, turning time was reduced by one-third or 8 s with the change from swallowtail turn to skipping a tramline (Demmel, 2007). Overlap was reduced in the practical test with a 4-m soil-cultivation device and 0.05 m steering precision by about 0.06 m in comparison with manual steering, and at the same time, the margin of fluctuation during steering was reduced (Berning, 2011). A tillage overlap of 0.1–0.2 m during the day and 0.4–0.5 m at night was reported for manual steering with a 6.8 m-wide implement on a commercial farm. With a guidance system, the overlap was reduced by 5–9% (Keller, 2005).

From the above-cited studies, we may conclude that the use of automatic parallel driving systems has positive effects in terms of drive performances and ergonomics. In most cases, however, the surveys were carried out only under experimental conditions on small rectangular-shaped patches with just one driver and using soil-cultivation devices without track markers. Measurements taken on commercial fields for various drivers as well as for seed drills with track markers are not available. It has not been verified whether turning times on commercial fields are actually reduced by 5–33%, nor whether vehicle working widths in the range of 1.3% to over 10% are better utilised.

In real-life surveys on the effects of automatic guidance systems, great importance is attached to driver relief as well as to the driving-performance aspects (Schulten-Baumer et al., 2009). This argument is also mentioned in almost all of the literature we have found on the subject, which claims that a driver expending 60% of his concentration on the steering process (Moitzi & Heine, 2006), experiences relief, and can better concentrate on controlling the equipment (Niemann et al., 2007; Rüegg et al., 2011; Schulten-Baumer et al., 2009).

We found in the literature few indications that the stress and relief experienced by tractor drivers has been explored in connection with the use of steering systems. One study comprised a task analysis for spraying operations by means of a questionnaire and observation of eye-glance behaviour and heart-rate variability. It showed that drivers preferred light bar and auto-steer navigation devices over alternative orientation techniques like foam markers, tramlines or flags. The trial design and data limitations did not allow for in-depth conclusions of driving with and without guidance systems (Dey & Mann, 2010). More clues were found in studies aiming to classify stress levels without direct physical exertion when the subject was driving a car, where heart rate was used as a measurement parameter (Egelund, 1982; Paridon, 2006; Reimer, Mehler, & Coughlin, 2010; Reimer, Mehler, Coughlin, Roy, & Dusek, 2011). At an initial heart rate of 71–77 min^{-1}, reacting to simple changes in street traffic resulted in a change of 1–2 min^{-1}; in more complex situations, the change was up to 6 min^{-1} (De Waard, 1996). Comparative measurements between manual and fully automatically controlled parking in mixed age groups between 20 and 60 years old showed heart rates to be 2 min^{-1} higher in the 10 s before and after the manual parking process than for automatic parking. During manual parking, heart rate increased by 12 min^{-1}, whilst during automatic parking it actually dropped slightly (Reimer et al., 2010). From studies on the use of mobile phones while driving a car, it emerged that heart rate increased significantly (NSC, 2010), or that in the case of younger drivers, heart rate rose temporarily during the call from about 70 to 74 min^{-1} (Reimer et al., 2011). Young drivers aged about 20 tested in the driving simulator with an initial heart rate of about 92 min^{-1} experienced an increase of 5 min^{-1} when instructed to solve simple brainteasers, enter something into their mobile phone, or carry out hazard braking. The drivers either did not notice the change in their heart rate, or did not experience the situation as more stressful (Paridon, 2006). The studies show that relief/stress whilst driving without direct physical exertion generally goes hand in hand with a change in heart rate of a few beats per minute, in individual cases even more. The relief/stress need not be experienced as such. It is uncertain whether similar effects occur whilst driving an agricultural vehicle with an automatic guidance system, and if so, to what extent.

The aim of the present study was to survey the effects of automatic satellite-based guidance systems on drive performance and ergonomic parameters in a fairly large trial under field conditions.

2. Materials and methods

2.1. *Trial design*

The primary tillage, seedbed preparation and sowing surveys took place in autumn 2010 and spring 2011 on commercial farms in various regions of the Czech Republic with a total of 17 drivers. The use of farm-owned guidance systems and drivers accustomed to handling the latter between one to three years allowed to rule out learning-related influences. The equipment used for primary tillage had working widths of 5–15 m, whilst the figure was 8 m for seedbed preparation and 6–9 m for sowing. The seed drills were equipped with track markers, whilst the primary-tillage equipment had no additional markers. Drivers were males of between 20 and 60 years old, the average age was 34 years (Table 1).

Measurements were carried out during 11–20 Oct 2010 with ten different drivers on 41 fields with sizes ranging from 1.2 to 8.5 ha, and in the period 16 Mar–19 Apr 2011 with seven different drivers on seven fields of size ranging from 11.7 to 49.2 ha. In the autumn campaign the fields were tilled either completely without or with guidance systems. In the spring campaign fields were subdivided into beds which were alternately tilled with and without guidance systems. Altogether, 66 plots ranging from 1.2 to 15.7 ha in size were considered in the analysis, with the average being 5.7 ha and the median 4.9 ha. Total surface area was 373 ha. Measurements were spread out over the day from 7 am to 12 midnight. No

Table 1 – Overview of tractors and equipment used and age of drivers.

Tractor manufacturer,[a] model	Equipment make, model, working width	Operation[b]	Driver's age
CASE Quad Track	Simba Xpress, 10 m	PT	20
Fendt 936	Horsch Terrano, 5 m	PT	26
CASE Quad Track	Horsch Tiger, 8 m	PT	31
CASE STX 450	Strom Swifter Combi, 15 m	PT	31
CAT MT 765B	Horsch Terrano, 5 m	PT	37
JD 8530	Strom Discland 6000, 6 m	PT	37
CASE Quad Track	Horsch Tiger, 8 m	PT	40
CASE Quad Track	Horsch Tiger, 8 m	PT	52
CASE Magnum 335	Horsch Terrano, 6 m	PT	60
JD 8220	Farmet Kompaktomat 8, 8 m	SP	34
JD 8220	Farmet Kompaktomat 8, 8 m	SP	34
CAT MT 765B	Horsch Phantom FG8, 8 m	SP	37
CASE 335	Great Plains, 6 m	S	22
JD 8530	Great Plains NTA 907 HD, 9 m	S	26
JD 8210	Lemken Solitär 10, 6 m	S	29
JD 8210	Lemken Solitär 10, 6 m	S	33
CASE 1170	Amazone EDX 6000-TC, 8 m	S	34

a Tractor manufacturers: JD = John Deere, CAT = Caterpillar.
b Operation: PT = primary tillage, SP = seedbed preparation, S = sowing.

automatic cruise control (Tempomat) which might have influenced the results was used.

Vehicles drove in straight parallel lines on all fields, except for one, where the vehicle followed the previous curved lane. Turning mode was chosen by the drivers according to the on-site conditions. Without a guidance system, omega curves were always used; with a guidance system, either omega curves or a lane-skipping approach was used. No swallowtail turning procedures were used (Fig. 1). During the turning operation, the driver steered manually and headed towards the next tramline according to the on-screen information.

A sampling ratio of about 50% without and 50% with guidance system was aimed at. In order to avoid disturbances during measurement, no one was allowed on the tractor except for the driver.

2.2. *Study parameters*

The field was subdivided into headland and main area. The turning operations took place in the headland, whilst the machine was in operation in the main area. The following parameters were investigated without/with the use of the guidance system during the primary tillage, seedbed preparation and sowing operations:

- **Driving speeds** in the main area and headland, based on the average values of the drivers.
- **Turning times**, based on the individual turning operations. Only the turning operations for which the conditions – especially field shape – were comparable when driving both without and with a guidance system were evaluated.
- **Steering accuracy** in the main area, based on the deviation from the target tramline calculated from the position points for the individual tramlines.
- **Utilisation of vehicle working width** based on field width, working width, and number of tramlines driven.
- As a measure of driver stress and relief, the **heart rates** in the main area and headland, based on the averages of the drivers.

For the heart-rate measurements, sports watches (Polar RS800CX, Kempele, Finland) with a chest-strap sensor and a polar satellite receiver (Polar G3 GPS Sensor, Kempele, Finland) with a position accuracy of ±0.3 m were used.

On all tractors satellite-based automatic guidance systems EZ-Guide 500 (Trimble, Sunnyvale, California, USA) with Real Time Kinematic Network correction (AgCelNet, Leading Farmers CZ a.s., Prague, Czech Republic) and an accuracy of ±0.025 m were used. One tractor was equipped with the Trimble EZ-Steer device mounted to the steering wheel, all others with a Trimble Autopilot being integrated directly into the vehicle's steering hydraulics. The nominal working width of the implement was used as guidance working width for tractors with Trimble Autopilot. For seedbed preparation after ploughing with the tractor with Trimble EZ-Steer and the Farmet Kompaktomat (nominal working width 8 m) the effective working width was set to 7.90 m. Satellite reception was stable during all measurements, with no reduction in

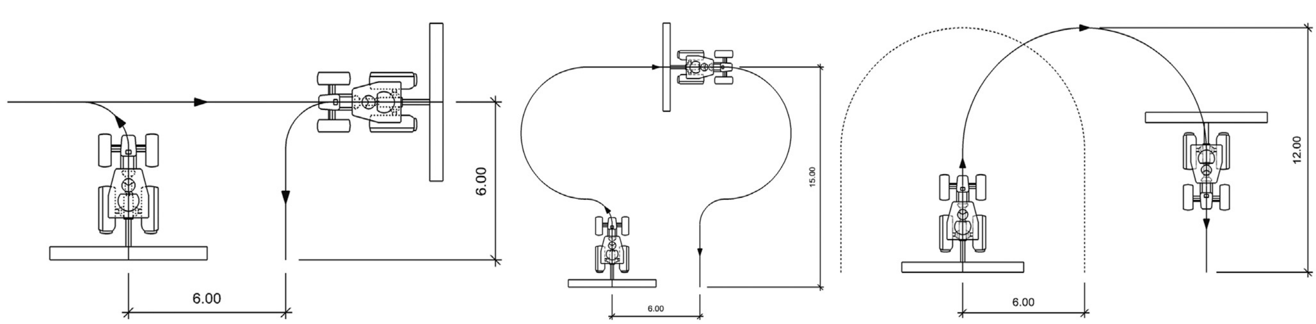

Fig. 1 – Left, turning in a swallowtail shape; middle, turning in an omega shape; in each case with a direct connection to the last tramline. Right: turning and skipping a tramline. Size of vehicle and lane exemplary.

accuracy. For technical reasons, no position data of the guidance system could be recorded in the autumn 2010 measurement. Instead, the position data from the Polar watch was used. In spring 2011, the guidance-system positions were recorded with a data logger (DD-Logger, CSM, Filderstadt, Germany) with a recording rate of 1 Hz.

A position point was stored every second on the route travelled by the tractor. The tilled field was then available as a point cloud. The chronological connection of the points showed the driving route.

The Polar watch files containing heart rate and position data were transferred into the Polar PC software (Polar Trainer 5, Polar, Kempele, Finland) and exported in Microsoft Excel file format (XLS). The position files from the polar watch and guidance system were imported into the Geographic Information System (GIS) Arc-GIS (Version 9.2, ESRI, Redlands, California, USA), whilst the satellite position data were transformed with the unit ‘metre’ into the S-JTSK Krovak coordinate system valid for the survey region, and headland and main area were saved separately and exported in XLS file format. The heart rate and position data from the polar watch and the guidance system were merged in Excel 2007 (Microsoft, Redmond, Washington, USA) on the basis of the exact-to-the-second time stamp. Distance measurements were carried out with the GIS Software QGIS (Quantum GIS Version 1.02, Open Source Geospatial Foundation (OSGeo), Beaverton, Oregon, USA). All further calculations of the study parameters and the creation of the figures were done with Excel.

As mentioned above, in order to determine the headland and main area, the corresponding points were stored separately in the GIS (Fig. 2). Because of this separation of the route, the position points are no longer available in continuous second intervals. Time leaps occur where the headland and main area were separated. A time difference of >1 s indicates the beginning of a new tramline or a new turning operation. In this way, tramlines and turning operations were counted and **turning times** were deduced.

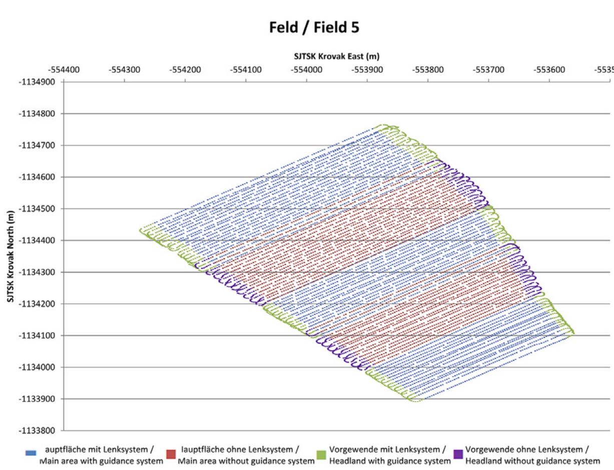

Fig. 2 – Exemplary position data (Driver Code field 37S8) in the Czech coordinate system S-JTSK Krovak; units in metres. Headland and main area were stored separately. Field size was measured in the GIS. The field is 712 m wide and the tramlines are 296–470 m long. Illustration is not to scale.

Driving speeds are contained in the satellite position data, and averages were created for the tramlines and turning operations.

To determine **steering accuracy**, the straight line of regression (=target tramline) was calculated from the position points of the individual tramlines driven. The residuals of the individual position points served as a measurement of the deviation from the target tramline.

Utilisation of vehicle working width was calculated on the basis of the tilled field or bed widths, whilst vehicle working widths were calculated according to manufacturer’s instructions and number of tramlines travelled.

Because of the aforementioned metrological problems in autumn 2010, suitable datasets for determining steering accuracy and utilisation of vehicle working widths were only available for spring 2011. Per driver and at two different places in the field, the field or bed width was measured crossways to the tramlines in six repetitions in each case, and the tramlines driven were counted.

2.3. *Statistical analyses*

For statistical analyses, TIBCO Spotfire S+® 8.1 for Windows (TIBCO Software Inc., Palo Alto, California, USA) was used with fixed-effects analysis of variance (ANOVA).

Altogether, values from 14 different drivers were analysed: 7 for primary tillage, 3 for seedbed preparation, and 4 for sowing. Since driver, field shape, etc. strongly influenced the measurement parameters, and not all drivers drove all vehicles for all operations, values were pooled based on the drivers and were not split up into operations. This yielded a randomised design with the fixed factors ‘Driver’ and ‘Driving with/without guidance system’ and the dependent variables ‘Driving Speed’, ‘Turning time’, ‘Steering Accuracy’, ‘Utilisation of Vehicle Working Width’ and ‘Heart Rate’.

3. Results

The differences in **driving speed** (main area: 4.1–11.0 km h^{-1}; headland: 4.8–12.6 km h^{-1}) could be explained by differences in tillage equipment, working depths, soils, drivers, and tractor performance. Drivers achieved on average more or less identical speeds both without and with a guidance system; there were no significant differences (Fig. 3). The greater margin of fluctuation in the headland is presumably attributable to the effects of field shape and differences in the lifting processes of the implements. Three hundred fifty turning operations by six drivers were used to calculate the **turning times** (Fig. 4). The average turning times without and with guidance system were 30 and 29 s, respectively. Differences were not significant. The in-some-cases high maximum values were attributable to factors to do with the natural landscape at the field margin, which extended the turning distance.

Two hundred one individual tramlines in the main area made by five drivers in spring 2011 were used to analyse **steering accuracy**. In the case of primary tillage and seedbed preparation, drivers steered more accurately with a guidance system than without. Accuracy rose along with increasing

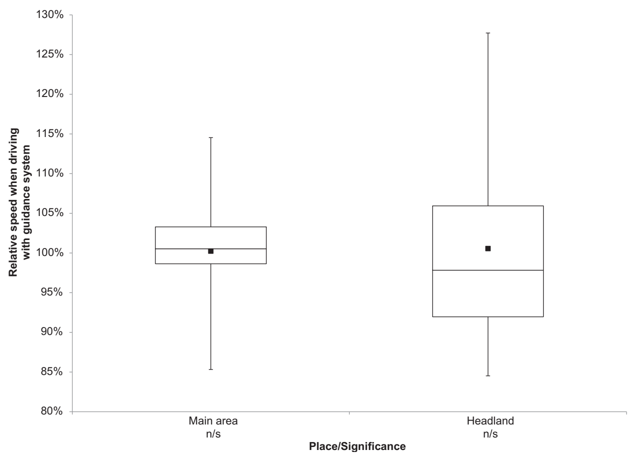

Fig. 3 – Relative speed when driving with guidance system, statistically analysed across all drivers. Speed without guidance system is 100%. Differences are not significant in either the main area or the headland. ■ = Average value; n/s = not significant. Upper, middle, and lower edges of the box indicate the lower quartile, median an upper quartile, respectively. Lower and upper whiskers show the minimum and maximum values, respectively.

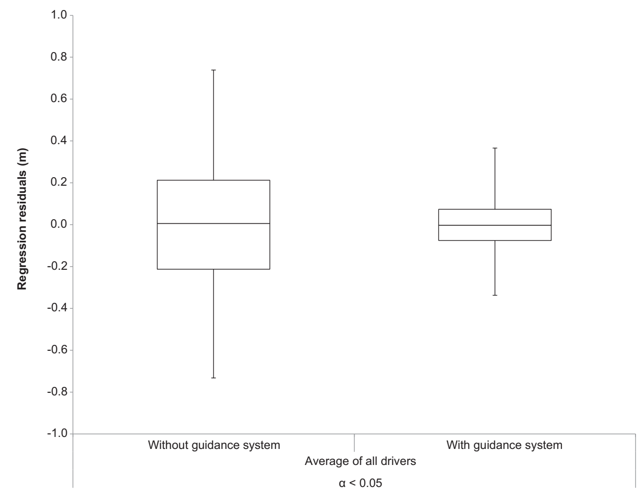

Fig. 5 – Steering accuracy when driving without/with guidance system as a boxplot of the regression residuals, i.e. deviation of the position points from the straight line of regression adopted as a target tramline. On average, differences were statistically significant. $\alpha < 0.05$ = Significant difference.

working width. For sowing without guidance system, the two drivers with track markers drove with a similar accuracy to those with a guidance system, or in a similar accuracy range to the drivers using a guidance system for primary tillage and seedbed preparation. The boxplot in Fig. 5 shows that the regression residuals used as a measure of steering accuracy (that is, the deviation of the position points from the straight line of regression adopted as the target tramline) decreased statistically significantly with a guidance system. The standard deviation of the regression residuals fell from 0.31 m without- to 0.12 m with guidance system. Figure 6 shows the **utilisation of vehicle working width** based on the data from six drivers and an average vehicle working width of 8.5 m. With a median of 99.1% without and 99.8% with guidance system, utilisation is very high in both instances. Without a guidance system, the driver usually drives with a slight overlap; with a guidance system, there are also skips. Based on the average vehicle working width of 8.5 m, the working-width utilisation with a guidance system is 0.04 m higher than without guidance system. Differences were not statistically significant.

Heart-rate averages ranged between 64 and 99 min^{-1}, the minimum and maximum values between 48 and 167 min^{-1}. Average heart rate was 84 min^{-1} in the main area and 86 min^{-1} in the headland. In both the main area and the headland, heart rates were in only a very few cases higher,

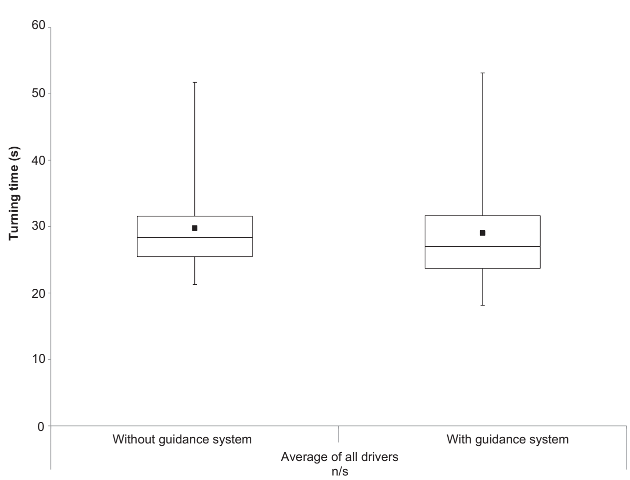

Fig. 4 – Turning times of a total of 350 turning operations with 6 drivers. Turning times with/without a guidance system did not differ significantly on average. ■ = Average; n/s = not significant.

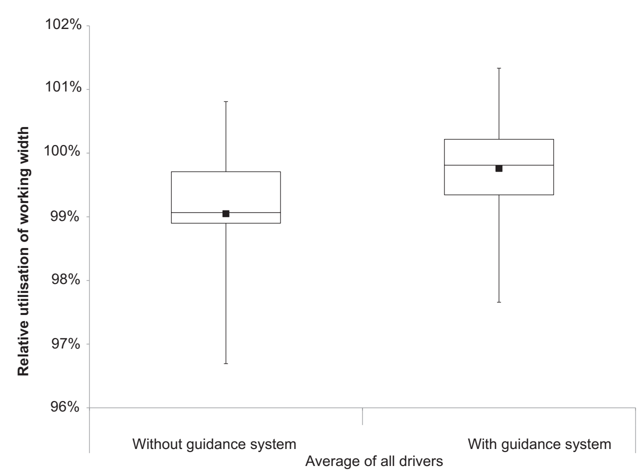

Fig. 6 – Relative utilisation of vehicle working width in per cent. Less than 100% means an overlap, more than 100% a skip. Differences were not significant. ■ = Average; n/s = not significant.

remained at the same level for a few drivers, and were lower for the majority of drivers with as opposed to without a guidance system. No trend towards a dependence of the operations was identified. Heart rate in the main area and headland fell on average by 2 min^{-1} or 2%, with differences being significant in each case (Fig. 7). With a median of 97.5%, relief in the headland was higher than in the main area, where the figure was 98.5%.

4. Discussion

Generally speaking, the use of a guidance system had no more than a minimal impact on **driving speed**. Given the large fields and working widths, other factors seemed to have been decisive here. The almost identical driving speeds in the field with and without a guidance system are presumably attributable to the fact that, regardless of whether or not a guidance system was used, drivers always attempted to drive at the maximum possible speed for the operation in question. Controlling connection accuracy did not have a limiting effect. No information on the impact of guidance systems on driving speeds was found in the literature.

For **turning times**, there were generally only minor differences in the existing experimental design with and without a guidance system. The marginally lower turning times measured with a guidance system can presumably be attributed to the fact that when driving with a guidance system, depending on factors to do with the natural landscape, turnings were performed in omega curves as well as with a skipped tramline, sometimes in the same field. In terms of time requirement, these two turning modes differ substantially less than a swallowtail-shape turn, which was never performed in the trial with the large working widths and surface areas. In the present trial, turning times were substantially more strongly influenced by parameters such as vehicle working widths and field shapes than by steering with or without a guidance system. The literature mentioned 5–35% lower turning times. The reduction by one-third was achieved by the change from a swallowtail turn to skipping a tramline. The 15% reduction per turning operation with a chisel plough in the rectangular field was also traced back to the turning mode used with the guidance system, where the tramline was skipped. The 5% reduction was recorded under similar field and machine situations to the present ones (Demmel, 2007; Kroulik et al., 2009; Moitzi et al., 2007). These surveys show that the savings for the same turning type are probably only marginal. Significant differences are to be expected when – given a small working width – the swallowtail turn can be avoided by skipping the tramlines.

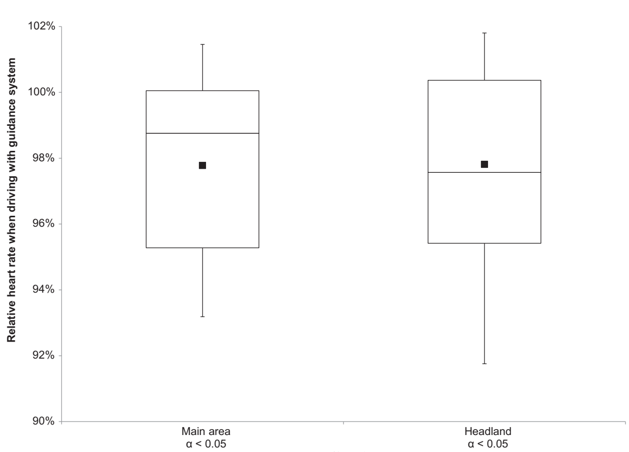

Fig. 7 – Relative heart rate when driving with guidance system, statistically evaluated across all drivers. Driving without guidance system = 100%. Driving with guidance system leads to significantly lower heart rates. ■ = Average, $\alpha < 0.05$ = significant difference.

With regard to **steering accuracy**, measurements showed that higher accuracies were in general achieved with rather than without guidance systems. The effect was quite pronounced for the primary-tillage and seedbed-preparation operations without track markers, but only slight for sowing with track markers. The low sample size of just three drivers for operations without track markers and two drivers for those with track markers is somewhat limiting for interpretation on the basis of the operations. Measurements found in the literature comparing equipment with/without a guidance system with equipment without track markers showed that greater steering accuracy is achieved with a guidance system. This tallies well with the current findings (Amiama-Ares, Bueno-Lema, Alvarez-Lopez, & Riveiro-Valiño, 2011; Berning, 2011; Gomez-Gil, San-Jose-Gonzalez, Nicolas-Alonso, & Alonso-Garcia, 2011; Macak & Nozdrovicky, 2011). Specific comparisons between manual and automatic steering during sowing were not found in the literature. It does, however, seem plausible that one could drive with track markers within a similar accuracy range to that of a guidance system. Essential for this are clearly visible markings, such as those found in the present case when sowing after seedbed preparation. At night and during fog, as well as in the case of direct drilling without prior tillage, the markings are either harder to see or scarcely visible, and guidance systems can bring about an increase in accuracy (Keller, 2005). A further aspect of the use of guidance systems are continuously straight drilling rows, which make it easier to use equipment for mechanical weed control as well as drop legs on plant-protection devices, which allow a reduction in the application rate at the same time as an increase in output quality (Rüegg et al., 2011).

In the present trials, the **utilisation of vehicle working widths** was increased by an average of 0.04 m via the use of guidance systems. This is less than in the literature, which reports a 0.06–0.15 m improvement in utilisation (Berning, 2011; Keller, 2005). For working widths between 6 and 15 m, 0.04 m seems relatively low, and the utilisation without a guidance system seems very high. The results should be attributable to the fact that the work was done on large-scale farms by professional drivers who achieved a very high working-width utilisation even without a guidance system.

The major differences in **heart rate** between the drivers are primarily attributable to their individual dispositions, and secondarily to the different requirements for operating the technology while driving. All in all, the drivers vary within a usual range; average values just over 60 can be considered to be fairly low and those around 100 fairly high (Dikow, 2010). The average 2 min^{-1} reduction in heart rate when driving with

a guidance system matches the heart-rate changes of 1–2 $\min^{-1}$ mentioned in the literature during adaptation to simple changes of situation in street traffic (De Waard, 1996; Winner, Halkuli, & Wolf, 2009); and the slight difference between positioning for parking and waiting for the automatic parking operation (Reimer et al., 2010). The change is not as great as a 4–5 $\min^{-1}$ increase in heart rate from being distracted during the journey (Paridon, 2006; Reimer et al., 2011) or during a manual parking operation of up to 12 $\min^{-1}$ more (Böhrnsen & Holtmann, 2011; Reimer et al., 2010). Although the measured differences seem low, it must be borne in mind that guidance systems scarcely change the degree of physical exertion, and that heart rate thus primarily indicates the change in mental strain. At two beats per minute, they correspond to the measured difference in heart rate between driving in the main area and in the headland. In other words, guidance systems reduce the strain to an extent that can be compared to the difference in strain between headland and main area. Slight changes of situation in street traffic such as lane changes, overtaking or turning led to similar heart-rate differences (De Waard, 1996) to those of the present measurements. Differences in this heart-rate range are rated positively (Keller, 2005; Moitzi & Heine, 2006; Niemann et al., 2007; Rüegg et al., 2011; Schulten-Baumer et al., 2009).

When interpreting the results of the study some limitations should be borne in mind.

Because it was not possible to record real time kinematic position data during the autumn campaign for technical reasons, the data for the analysis of turning times and working-width utilisation were based on only six and five drivers, respectively. Thus, low statistical power could be the reason behind the lack of statistical significance.

For organisational reasons it was neither possible to measure the same driver at different tasks, nor to carry out long-term measurements over full working days or during full day- and night shifts. Observation periods were between 1.1 and 2.8 h per driver. Statements with respect to the effects of guidance systems in the case of longer driving times or different concentration and visibility conditions during the day and at night are therefore only possible to a limited extent. With longer deployment, driving performance and ergonomic effects might differ. It may be presumed that steering accuracy and utilisation of vehicle working width in particular would tend to decrease with a longer working time, poor visibility conditions and at night-time, but that it would nonetheless be possible to work consistently accurately with a guidance system.

It can also not be ruled out that the drivers we studied may have behaved differently in the observed situation, e.g. they may have driven with greater concentration, thereby achieving a better quality of work than would have been the case in the everyday situation.

The ergonomic analysis based on heart-rate measurements was rather basic. To capture driver's stress levels and mental workload generally the use of more advanced physiological indices like electroencephalography (EEG), facial electromyography (EMG) or eye-movement measurements would be reasonable. In this case of a practical oriented field trial under real-world conditions with short time slots for measurements it was difficult to employ such more sophisticated techniques. Whilst planning the field trial it became clear that there would be a trade-off between measurement techniques and practicability and that only easy-to-use measurement methods would be applicable. However, in order to deliver more authoritative results, future studies should be based on more objective physiological indices and should also take advantage of driver's self-report of the level of stress and mental workload.

5. Conclusion

In the present 17-driver study investigating the operations of primary tillage, seedbed preparation and sowing, the guidance-system effects measured were for the most part slight. Driving speeds in the headland and in the main area, turning times and utilisation of vehicle working widths were in some cases slightly more advantageous with a guidance system than without, but did not differ significantly from one another. Working widths, driver, and factors to do with the natural landscape – such as field shape and optimal turning strategies resulting therefrom – had a substantially greater influence in the practical trial on the measurement parameters than did the use of a guidance system.

With the use of guidance systems, steering accuracy increased statistically significantly. This effect was substantially more pronounced when working without track markers and for large working widths than for sowing with track markers and with clearly visible lane markings. Advantages during sowing arise when lane markings are scarcely visible, such as during night-time work or with direct drilling.

The statistically significant effect of a slight heart-rate reduction of the drivers demonstrated that the comfort and ergonomics of tractor jobs may increase with the use of guidance systems. Drivers may remain efficient for longer, and quality of work may remain at a consistently high level.

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